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Flood hazard mapping in Southern Brazil: a combination of flow frequency analysis and the HAND model

Gustavo Andrei Speckhann¹, Pedro Luiz Borges Chaffe²*, Roberto Fabris Goerl³, Janete Josina de Abreu⁴, Juan Antonio Altamirano Flores⁵

¹Graduate Program of Environmental Engineering, Federal University of Santa Catarina – UFSC, Florianopolis-SC, Brazil; email: gustavo.speckhann@posgrad.ufsc.br
²Department of Sanitary and Environmental Engineering, Federal University of Santa Catarina – UFSC, Florianopolis-SC, Brazil; email: pedro.chaffe@ufsc.br
³Department of Natural and Social Sciences, Federal University of Santa Catarina – UFSC, Curitibanos-SC, Brazil. Email: roberto.f.goerl@ufsc.br
⁴Department of Geosciences, Federal University of Santa Catarina – UFSC, Florianopolis-SC, Brazil email: janete.abreu@ufsc.br
⁵Department of Geosciences, Federal University of Santa Catarina – UFSC, Florianopolis-SC, Brazil; email: juan.flores@ufsc.br

*Corresponding author.

Abstract

The Itajaí River basin is one of the areas most affected by flood-related disasters in Brazil. Flood hazard maps based on digital elevation models (DEM) are an important alternative in the absence of detailed hydrological data and for application in large areas. We developed a flood hazard mapping methodology by combining flow frequency analysis with the Height Above the Nearest Drainage (HAND) model – f2HAND – and applied it in three municipalities in the Itajaí River basin. The f2HAND performance was evaluated through comparison with observed 2011 flood extent maps. Model performance and sensitivity was tested for different DEM resolutions, return periods and streamflow data from stations located upstream and downstream on the main river. The flood hazard mapping with our combined approach matched 92% of the 2011 flood event. We found that the f2HAND model has low sensitivity to DEM resolution and high sensitivity to area threshold of channel initiation.

Key words flood hazard; flow frequency analysis; HAND model; DEM

1 INTRODUCTION

Life and monetary losses related to floods are a major concern worldwide and have grown considerably during the last few decades (Kundzewicz et al. 2012, Arrighi et al. 2013, Blöschl et al. 2015, Sayama et al. 2015). This increase is probably a combination of: (a) better reporting of flood disasters (Peduzzi et al. 2012); (b) higher exposure and vulnerability of socioeconomic receptors (Moel et al. 2009, Hall et al. 2014, Kundzewicz et al. 2014); and (c) possible
alterations in climate natural variability (IPCC 2012). The costs related to flood damage are classified in several categories (Meyer et al. 2013) and can sum up to billions of Euros very quickly (Moel et al. 2009, Arrighi et al. 2013).

The assessment of natural hazards has shifted from the analysis of historical records of losses to model-based risk assessment (Hall et al. 2015). Flood risk mapping is one of the tools to help communities avoid or mitigate such losses and damages (Arrighi et al. 2013, Savage et al. 2014). The European Parliament established that flood risk maps should be done at the level of river basin district, in order to provide an “effective tool for information” (European Parliament, 2007).

Hydrodynamic models such as HEC-RAS (USACE-HEC, 2000), MIKE FLOOD (DHI, 2007) and LISFLOOD-FP (Bates & De Roo 2000, Bates et al. 2010, Neal et al. 2012) have been widely used to elaborate flood hazard maps and are the common choice for estimating inundations (Savage et al. 2014). The combination of rainfall–runoff–inundation is another possibility for flood mapping (Sayama et al. 2012, Ushiyama et al. 2014, Sayama et al. 2015). Some of these models have even incorporated the economic damages (Kobayashi & Takara 2013, Kobayashi et al. 2014). Although the level of detail in flood modelling may have risen (e.g. Neal et al. 2011, Neal et al. 2012, Lee et al. 2015), the computational costs and data requirement might deem them unsuitable for larger areas. Besides that, the uncertainty in deterministic flood risk mapping should not be neglected (Pappenberger & Beven 2006, Beven et al. 2014) even when derived using physically-based models (DiBaldassarre et al. 2010).

Flood hazard maps based on digital elevation models (DEM) and geomorphic features (e.g. slope, distance to the nearest divide and topographic index) have been developed as a prompt low-cost alternative in the absence of detailed hydrologic and hydraulic data and for regions of large extent (Noman et al. 2001, Manfreda et al. 2011, Degiorgis et al. 2012, Nardi et al. 2013, Jalayer et al. 2014, Manfreda et al. 2014, Pourali et al. 2014, Samela et al. 2015). Those terrain descriptors have also been used worldwide for mapping flood hazard with regard to climate change (Kwak & Kondoh 2010, Kwak et al. 2012) and for downscaling inundation maps at the regional (Bwangoy et al. 2010) and global scales (Fluet-Chouinard et al. 2015). The basic idea is that a simplified inundation algorithm can be effective when grounded in hydrogeomorphic theory (Nardi et al. 2006, Manfreda et al. 2015).

The best performing geomorphic classifiers were found to be: (a) the difference in elevation from any point on the terrain to its nearest downstream drainage point (Degiorgis et al. 2013, Manfreda et al. 2014, 2015, Samela et al. 2015); and (b) the composite index which considers the logarithm of the ratio between the water level at any point and the difference of elevation to its nearest downstream drainage (Manfreda et al. 2015, Samela et al. 2015). Those two geomorphic indices were able to correctly classify more than 90% of the flood-affected areas (Degiorgis et al. 2012, 2013, Manfreda et al. 2015, Samela et al. 2015). However, in order to
more accurately identify the non-flooded areas, it is important to consider the hydrogeomorphic classifier that also uses design flood peak at the basin outlet (Nardi et al. 2013, Manfreda et al. 2014). The composite index proposed by Manfreda et al. (2015) built on some of the work of Nardi et al. (2006, 2013) and seemed to be more consistent in mapping flood-affected areas in both regions of steep and gentle slopes, and also less sensitive to DEM resolution.

The Height Above the Nearest Drainage (HAND) model is a terrain descriptor that calculates the difference in elevation of each pixel and its nearest drainage point (Rennó et al. 2008). The model has been applied to Amazonia, where it was calibrated and validated by establishing a relationship between soil water conditions and drainage potential (Rennó et al. 2008, Nobre et al. 2011, Cuartas et al. 2012). It was also used in landscape classification to distinguish different runoff characteristics as an input in hydrological modelling (Gharari et al. 2011, Nijzink et al. 2016). Liu et al. (2016) used HAND in order to derive a high resolution flood map for the entire USA. In Southern Brazil, HAND has been applied as a tool for flood mapping (Nobre et al. 2015, Momo et al. 2016). Nobre et al. (2015) proposed the creation of a proxy predictor of inundation extent, HAND contour, which connects points with the same normalized flood stage.

Flood-related disasters are under high concern in the Southern Brazilian region. In Santa Catarina State, there were 1257 flood occurrences between 1980 and 2010 (Herrmann et al. 2014). It is estimated that floods resulted in 38 deaths, 948 injured and 175 130 unsheltered people during the period 2000–2012 (CEPED 2012). The Itajaí River basin can be considered as the area most affected by flood disasters, where cities like Blumenau, Gaspar and Ilhota have been suffering with the negative consequences of floods.

Other recently severe hydrological disaster occurred in the Complexo do Baú that is located inside Ilhota domains and experienced huge calamity during a 2008 extreme event. Flood hazard mapping of this area was performed by combining design rainfall with HEC-HMS and FLO-2D models (Monteiro & Kobiyama 2013, 2014). That methodology may suffer significant alterations due to changes in rainfall temporal distribution and Curve Number values. Previous studies (Nobre et al. 2015, Momo et al. 2016) applied the HAND contour as a proxy predictor of inundation extent for Blumenau and Brusque municipalities. Model accuracy reached 86-98% when compared to flood extent maps. However, none of these studies incorporated any information regarding flood frequency.

In this paper, we developed a flood mapping methodology at the municipality scale by combining flow frequency analysis with the HAND model – f2HAND. It is a hydrogeomorphic methodology similar to the ones proposed by Nardi et al. (2013) and Manfreda et al. (2015). The f2HAND model performance for flood hazard mapping was evaluated through comparison with observed flood extent maps. Some of the questions that we analyzed were:
(a) What is the sensitivity of the f2HAND to DEM resolution and drainage threshold values?

(b) Does the location (downstream or upstream) of streamflow record affects the estimates?

Data from different stations located on the main river were used to explore whether regionalization techniques would interfere in the probable inundation map.

2 MATERIAL AND METHODS

2.1 Study area

The Itajaí River Basin is 15,000 km² and is located in the Santa Catarina State, Southern Brazil (Fig. 1). The climate is classified as Köppen Cfa (Kottek et al. 2006) with average annual rainfall of 1610 mm. The number of people living in Itajai-Açu basin is nearly 1.5 million (IBGE 2010).

Structural flood protection measures in the Itajaí Basin include three dams (Silva et al. 2014). The Oeste Reservoir, with a capacity of 83 hm³, was finished in 1973 and is located at the city of Taió; the Norte Dam was finished in 1992 and is the biggest, with a full storage capacity of 357 hm³ and is situated at the city of José Boiteux; and the Sul Dam is located in Ituporanga municipality with 89 hm³ storage capacity. The Itajaí basin is frequently under extreme rainfall generating weather types, where floods are associated with extreme rainfall, and prone to occur during both summer and winter (Martins and Clark 1993).

The population of Gaspar and Ilhota, respectively 66,000 and 13,000 inhabitants, presents a lower population density than Blumenau. Besides their population aspects, an extensive part of the urban territory of Gaspar and Ilhota is comprised of floodplain. Blumenau, in contrast, has an urban area characterized by significant high slope areas (Fig. 1). Even though Ilhota had a massive landslide at Morro do Baú during the 2008 event, floods are a more pressing issue for Gaspar and Ilhota due to floodplain occupation at the Itajai-Açu River bank.

Reports from the Gaspar and Ilhota authorities highlight the high exposure of the municipalities, even for events with short return periods. The urban area of Blumenau is 206.8 km², which corresponds to 38% of the entire municipality. Within the urban area only a fraction is affected by inundation. The 2011 water level event in Blumenau reached 13 m, affecting nearly 30% of the urban area.

Blumenau, Gaspar and Ilhota municipalities have been suffering from flood events since the first settlements, and are considered three of the most affected locations in the basin. The population memory regarding flood risk is easily activated whenever extreme rainfall occurs. Blumenau (population: 338 thousand) has a record of 77 events greater than the 8-m flood level since 1852. The 8-m level corresponds to the return period of less than 2 years. At this level, at least 180 buildings are affected by inundation in the city of Blumenau (Refosco et al.
Ilhota suffered a major tragedy in 2008: extreme rainfall triggered a severe event of floods and landslides at the Morro do Baú locality, resulting in major damages and loss of lives.

2.2 DEM Data and flood extent maps

After a severe flood that occurred in 2008, the State of Santa Catarina, through the Secretary of Sustainable Development (SDS), elaborated a very high 1-m resolution DEM (SDS-DEM) with vertical accuracy compatible to the 1:10 000 scale. This is a unique dataset since, until 2014, the SRTM (Shuttle Radar Topography Mission) DEM of 3 arc-seconds and about 90 m resolution was the only topographic dataset freely available for the entire Brazilian territory. Recently, the 1 arc-seconds void-filled SRTM DEM (about 30 m resolution), was released to the entire world (USGS 2016). In Brazil, the 3 arc-seconds void-filled SRTM DEM has an accuracy compatible to the 1:100 000 scale (Souza & Loch, 2008; Miceli et al., 2011). In the void-filled DEM, the main inconsistencies in the elevation data were removed and filled using other elevation sources or interpolation algorithms (USGS, 2016; Digiorgis et al., 2013). Despite the coarser resolution of the 3 arc-seconds SRTM DEM, relatively accurate flood-prone area maps can be obtained by using this SRTM DEM-based method (Manfreda et al., 2011, Digiorgis et al. 2012, Nobre et al. 2015).

We analysed the influence of different DEM sources and resolutions in the proposed f2HAND model. The SDS-DEM was re-interpolated in ArcGIS software using the resample tool and the bilinear algorithm that determines the new value of a cell based on a weighted distance average of the four nearest input cell centres. The re-interpolated DEMs of 3, 5, 10, 20 and 30 m resolution were used as input for the f2HAND flood maps as were the 1- and 3-arc-seconds SRTM DEMs.

All DEMs were pre-processed in TerraHidro software\(^1\), in which the HAND model is fully integrated. The stream network is key, since the elevations of the drainage network pixels are used to calculate the normalized terrain heights. In order to overcome DEM irregularities when calculating flow direction, HAND uses the breaching method – similar to O’Callaghan & Mark (1984), to solve and generate a corrected local drain direction.

The first step in the DEM pre-processing is to make a hydrologically consistent DEM by filling the sinks and gently burning the DEM. The consistency processes is aimed at preventing a downward slope along the flow path. The depression filling algorithm finds no-flow cells and adopts two solutions: (i) focusing on the flat areas, where the no-flow cells are caved; and (ii) filling the remaining sinks. The process of flow-path correction changes the pixel elevation

from the edge to the centre of the flat area. The value of all pixels in the flat area is decreased by $10^{-4}$ m until a V-shaped channel is formed.

The filled DEM is used in the calculation of the flow direction using the D8 algorithm as well as the flow accumulation. Officially flood extent maps were used to compare f2HAND results and its sensitivity to drainage density and DEM resolution. Two hydrography extracts were made available: one at the scale 1:10 000 (provided by SDS) and the other at 1:50 000 (provided by the Agricultural Research and Rural Extension Company of the State of Santa Catarina) (Fig. 2(a)).

The drainage network was then extracted from the DEM according to several thresholds of channel initiation (e.g. Fig. 2(b)). The filled DEM, the flow direction and the drainage network are the main inputs to the HAND model.

The flood hazard maps were validated using the flood extent of different events with different return periods. The 10-, 11- and 12-m flood extents are the official flood-prone areas used by the Civil Defense in the Blumenau Flood Warning System (Fig. 2(c)). The 13-m flood-prone area was obtained by Refosco et al. (2013) who mapped more than 330 points of the 2011 flood extent area in Blumenau with a Geodesic GPS. The survey was done after the events, using pictures, flood marks in infrastructure, and reports from residents affected by floods as a proxy for flood records (Refosco et al. 2013).

The flood extent is more uncertain in floodplain areas (Nardi et al. 2006, 2013 & Manfreda et al. 2015). One of the potential drivers of floodplain uncertainties are DEM inconsistencies, which forces the HAND algorithm to inadequately carve a water path, leading to incorrect stream network tributary definition.

### 2.3 Stage–discharge data and flow frequency analysis

The streamflow data was obtained from the Brazilian National Water Agency—ANA (www.hidroweb.ana.gov.br). There is one fluviometric station located along the main river in each of the three municipalities. Blumenau station had the largest registry of the three (76 years of record); Gaspar station had 66 years of record; and Ilhota 18 years.

Flow frequency analysis is essential in flood risk assessment (Renard et al. 2013). The common procedure associates a possible flood occurrence with a return period which is calculated from the observational data (Mei et al. 2015). One of the challenges of this analysis is to associate an extreme distribution that reasonably fits the observed data (Maidment 1992). Following the recommendation of several authors (e.g. McCuen 1941, Maidment 1992, Naghettini & Pinto 2007, Ashkar & Aucoin 2012), the flow frequency analysis was performed using four distributions: GEV, log-normal, Gumbel and log Pearson 3.

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Since three flood protection dams were built upstream in the Itajai River basin, we tested the stationarity of annual maxima of flood series of all three stations (Blumenau, Gaspar and Ilhota) using a linear function. Koutsoyiannis (2006) described the linear function approach as the simplest possible and the most widely used to model hydrological trends. A significant trend is determined when the model slope term is at a significance level of 0.05 or less ($p < 0.05$), computed using a one-sided Student’s $t$-test (Vogel et al. 2011).

The bias and standard error of the distributions were calculated by using a Jackknife method. Jackknife is a technique that consists of an iterative process to estimate a parameter from a sample, where no parametric assumption is needed. First, the statistic of interest is estimated from the whole sample ($T$). Next, each element of the sample is dropped, one at a time, and the parameter of interest is estimated using the remaining elements $T'$ (Martinez & Martinez 2002). The average, bias and standard error can be calculated as:

$$\bar{T}^j = \frac{1}{n} \sum_{i=1}^{n} \frac{T^i}{n}$$

where $n$ is the sample size and $\bar{T}^j$ is the average of the Jackknife replications. The estimate of standard error ($\text{SEjack}(T)$) is calculated as:

$$\text{SEjack}(T) = \left[ \frac{1}{n} \sum_{i=1}^{n} (T^i - \bar{T}^j)^2 \right]^{1/2}$$

(2)

The estimate of $\text{Biasjack}(T)$ is calculated as:

$$\text{Biasjack}(T) = (n - 1)(\bar{T}^j - T)$$

(3)

2.4 f2HAND: Combining flow frequency analysis with the HAND model

The HAND model calculates the height of each cell in a DEM raster in relation to its nearest drainage point (Rennô et al. 2008, Nobre et al. 2011). The model uses the drainage network and the local drain directions to create the distance to the nearest drainage map, which is the normalized topology of the HAND model (Rennô et al. 2008, Nobre et al. 2011). The HAND model is basically a terrain descriptor and therefore it cannot estimate the flood wave as in the case of hydrodynamic models. The water surface is considered as horizontal due to lateral hydrostatic equilibrium, which leads to an estimate limited to the maximum extent of a stationary flood (Nobre et al. 2015). In practice, the lateral hydrostatic equilibrium implies that if a pixel value is lower than the water level height, that pixel is considered as a flooded one.

The flow frequency analysis of historical records was combined with HAND to create a flood hazard map (Fig. 3). We call this approach the f2HAND, which consists of four main steps:
(a) Flow frequency analysis: select annual maxima from the streamflow record and apply the flow frequency distribution.

(b) Application of the HAND model: correct the hydrological inconsistencies from the DEM, generate flow direction and flow accumulation, extract the drainage network through a threshold and calculate the height above the nearest drainage (HAND).

(c) Referencing the height of a specific staff gauge: establish the equivalency between the HAND model grid and the location where the water level was measured. Figure 4 shows the procedure to connect the staff gauge height and the normalized height calculated by HAND.

(d) Combination of flood frequency and HAND model (f2HAND): select the return period values and the distribution to slice the surface generated by HAND, and generate the probable inundation map. The return period of a probable flood map is associated with a reference water level. The classification of areas affected by low return periods is likely an effective way to identify possible flood prone areas.

The correspondence of the HAND raster with the water level is an essential aspect in the f2HAND method. In order to achieve that, high-precision georeferenced measurements in the field are required. For a specific gauge height, it is important to establish the equivalence of the raster generated with HAND (Fig. 4(a), (b), (c)) and the water level of the staff gauge (Fig. 4(d)). The difference between the HAND raster and the stage height (e.g. water level at 7 m) should be added to the distribution (Fig. 4(e)), so that the height from the flow frequency analysis matches that calculated with HAND (Fig. 4(f)). Neglecting the previous step is likely to lead to incorrect estimates of the inundation extent. The yellow squares in Figure 4(f) represent the inundation extent for a 10-year return period without matching the height. The red contour pixels represent the inundation extent of a 10-year return period when the height of staff gauge matches the HAND raster.

### 2.5 Sensitivity analysis

The results of the f2HAND approach were submitted to a conditional evaluation where each input cell of the raster received a signature: 1 for flooded area and 0 for non-flooded. A raster operation was realized by combining the flood extent from 2011 (13 m) and the f2HAND model results. If the flooded area was correctly identified by the model, the cell was assigned as 2 (True Positive). If the model overestimated the flood extent (i.e. False Positive), we assigned the value –1, and if the model underestimated the flooded area (i.e. False Negative), we assigned 1. The value –2 was assigned to cells that were considered True Negative, meaning that both the model and the flood extent indicated that the cell represents a pixel that is affected neither by the floods nor by model underestimation or overestimation. This method was used to compare
different DEM resolutions (e.g. 3 m, 5 m, 10 m, 1 arc-seconds) to the 10-, 11-, 12- and 13-m official flood-prone areas of the municipality of Blumenau.

The Receiver Operating Characteristics (ROC) graph is a technique to quantify classifiers according to their performance (Fawcett 2006). This approach has been widely applied in medicine, and studies in floodplain identification have also implemented as a tool to evaluate the classifier’s performance (Degiorgis et al. 2012, Manfreda et al. 2014, 2015). The ROC procedure in this paper is very similar to the one applied by Manfreda et al. (2015), in that the f2HAND results were compared to the 2011 flood event in Blumenau Municipality using different DEM resolutions (e.g. 5, 10 and 30 m).

The ROC values are calculated by the plot of the True Positive ($r_p$) and False Positive ($r_n$) rates, which are plotted on the y- and x-axes, respectively.

$$r_p \approx \frac{\text{Positive correctly classified}}{\text{Total positives}}$$

$$r_n \approx \frac{\text{Negative incorrectly classified}}{\text{Total negatives}}$$

3 RESULTS AND DISCUSSION

3.1 Flow frequency analysis

The flood wave usually affects Blumenau first and later diffuses to Gaspar and Ilhota. In fact, Gaspar and Ilhota stakeholders use the Blumenau staff gauge as a reference to predict and monitor the inundation evolution on their own territory. The annual maxima records of the three stations (Blumenau, Gaspar and Ilhota) were used to calculate the parameters of four different extreme distribution types (Fig. 5).

The distributions were tested using the Jackknife method and revealed low bias and standard error values. The peak flow discharge was estimated using Gumbel distribution. The bias and standard error values for Blumenau were –0.004 and 0.032 m, respectively. The Gumbel distribution was also used to estimate peak flow values for Gaspar and Ilhota. Although negative trends were found in the streamflow data, we have not considered this information for the flood frequency analysis. For all cases we have adopted the assumption of stationarity.

3.2 f2HAND flood-prone area map

The f2HAND model represented 92% accurately the 2011 flood extent using a 5-m DEM resolution. The simulated inundation reach for a 2-year of return period was 13.8%, while it was almost 25% for a 20-year return period using a 3-m resolution DEM.

The user ability to comprehend and correctly consider the uncertainties of the flood hazard mapping may demand a level of expertise which may not be common ground to every model
user. When the user applying the model is not familiar with technical vocabulary, one approach to avoid error is to simply classify the probable inundation map into three categories of hazard: High (return period < 5 years), Medium (5 years > return period < 25 years) and Low (return period > 25 years) (Fig. 6).

3.3 f2HAND sensitivity to the area threshold for channel initiation

The application of the HAND classifier has the advantage of being simple to set, since the only modification is to alter the channel initiation threshold (Degiorgis et al. 2012). The use of thresholds similar to the official hydrography (Fig. 2(a)) implies an increase in the percentage overestimation of the inundation map, since, given a certain limit – for coarser resolution DEMs – all cells would be nearer to the drainage network and could be considered flood-prone areas. This may be a sign that there is an optimum channel size that would control the flood process, which can be very helpful to extend the flood map to other sub-basins in the same area.

The appropriate choice of area threshold for drainage generation is important for inundation mapping since river channels are used to normalize the DEM in the HAND process. Neglecting this step can lead to substantial errors in the estimates of inundated areas. Four thresholds were specifically tested: 0.45 km$^2$ (the same as Nobre et al. 2015); 2.4 km$^2$; 4.05 km$^2$ (the same as Nobre et al. 2015); and 6.71 km$^2$ (Fig. 7). Using a smaller area threshold increased the overestimation of the flooded area from 12% to 24% when compared to the 6.71 km$^2$ threshold. However, the threshold impact over underestimation is not expressive. The difference between using a 10 times higher threshold was less than 1%. Both overestimation and underestimation have a tendency to stabilize when reducing the drainage density (Fig. 7).

The ROC curves (Fig. 8) present a general description of the f2HAND algorithm’s ability to identify flood-prone areas using different channel initiation thresholds of official flood-prone areas. The results are consistent with previous findings, and confirm that an increase in the height above the nearest drainage corresponds to a lower hazard level (Degiorgis et al. 2012, Manfreda et al. 2014). We tested the model performance against four official flood extent maps (10, 11, 12 and 13 m), while varying the area threshold. For high hydrographic densities, the overestimation (False Positive) increases. The ROCs (Fig. 8) show that using the height above nearest drainage performs well in the assessment of flood-prone areas; the same results were obtained by Degiorgis et al. (2012) and Manfreda et al. (2014).

The f2HAND model presented low sensitivity related to the return period of the flood extent. In Figure 8, one cannot easily identify which curve presents the best fit. Nonetheless, the accuracy using a 5 m × 5 m DEM with a threshold of 4.05 km$^2$ was at least 87%, independent of which flood hazard map was being compared.
3.4 f2HAND sensitivity to different DEMs

A high-resolution DEM might be a computational burden when using the HAND model. The f2HAND model has low sensitivity to DEM resolution (Fig. 9) and model performance is mainly related to the DEM source. Our results showed that the coarser 30-m resolution DEM matched nearly 90% of the flood extent of the 2011 event in Blumenau.

The ROC curves (Fig. 10) are associated with the binary classifier, HAND, obtained by separately thresholding channel initiation values for different DEM sources (e.g. SDS and SRTM) and resolutions (e.g. 3, 5, 10, 20 and 30 m). The results were defined in terms of False Positive and True Positive rates, compared to the official 13-m flood extent of 2011 in Blumenau municipality. Much more important than the DEM resolution (pixel size), and the core aspect related to performance, is the scale/source (SDS and SRTM) of the DEM (Fig. 10).

Both SRTM DEMs (1 and 3 arc-seconds) presented very similar and satisfactory results (88%) and all re-interpolated SDS DEMs also had similar accuracy values. The main differences are in the False Positive and True Positive values. For this specific case, the SDS DEM provides a more accurate performance when compared to the SRTM 1 and 3 arc-seconds DEMs. Similar findings were also registered by Manfreda et al. (2011) using coarse pixel size. The re-interpolated SDS DEM also reached high accuracy values. Using a 0.4 km² area threshold, the true positive values for 1 and 3 arc-seconds were 0.76 and 0.79, respectively, and for the 5-m resolution SDS it was 0.93.

Even though the accuracy of the model using SDS or SRTM DEMs were close, for all stations and distributions tested (log-normal, log Pearson, Gumbel and GEV), the percentage of simulated flooded area using 1 and 3 arc-seconds had a lower performance than the re-interpolated DEM from SDS. One of the possible reasons for such differences is the inability of the model to generate the correct drainage. That may happen because the study was done for each municipality instead of at the basin scale. Therefore, processes such as flow accumulation and flow direction may induce irregularities at the drainage channel.

3.5 f2HAND sensitivity to the choice of extreme value distribution

In order to understand how the f2HAND methodology would perform in larger areas and using data provided by regionalization, we tested the impact of using data from gauge stations located upstream and downstream of the municipalities studied.

By using binary classifiers we compared the performance of using 20-year return period Gumbel distribution values from Gaspar and Ilhota gauge records and applied it to Blumenau to compare with the 13-m flood extent from the 2011 event. The aim was to comprehend whether distribution values from upstream and downstream stations – having the same main river in
common – could be transposed through regionalization methods to nearby stations in the case of missing data.

The application of the Gumbel distribution of 20-year return period values from Gaspar and Ilhota presented an alternative in the case of missing data in an upstream gauge (Blumenau). Both sites – for a low return period value – were able to match approximately 90% of flood extent (Fig. 11), similar to the results obtained by Degiorgis et al. (2013) and Manfreda et al. (2014). Nevertheless, the distribution selection can largely impact the simulated flooded area, which means that the application of regionalization techniques needs to be done with extreme care in order to be correctly executed.

4 CONCLUSIONS

We have proposed a flood hazard mapping methodology that combines flow frequency analysis of annual maxima with the HAND model – f2HAND. We applied that methodology in Southern Brazil at three municipalities most affected by floods in Santa Catarina State. The flood hazard map was tested against the official flood hazard maps of Blumenau.

The derived 20-year flood hazard map elaborated with the f2HAND model, matched approximately 90% of the flood extent from the 2011 extreme event at Blumenau. The model ability to match the flood extent was similar to the performance of previous work that used the same morphological classifier in other parts of the world.

The f2HAND model presented high sensitivity of area threshold to channel initiation, which can be an indication that there may be an optimum channel size that would regulate the flood process. Regarding the use of DEMs, the f2HAND model had low sensitivity to resolution – no major disparity was observed for different DEM resolutions, but results may vary depending on the source of the selected DEM.

The use of streamflow data from downstream and upstream stations may result in overestimation of the flood hazard inundation map. The application of streamflow data from different locations (e.g. upstream, downstream and regionalization from other basins) should be done parsimoniously, since the results may change drastically from one station/municipality to another. Extrapolation discrepancies may be avoided by selecting the longest streamflow record available and by choosing stations as close as possible to the study site.

We believe the f2HAND model can be an effective tool for city management and disaster prevention. The approach does not have high computational requirements. Simple preliminary results may be a valuable tool to identify hotspots for more detailed inundation studies. The model opens the possibility to merge soft and hard data by introducing information collected from the local population about previous inundation records.

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Figure captions

**Figure 1.** Location and slope map of the three sites studied. Inset: the hypsometric curve of each site.

**Figure 2.** (a) Official hydrography provided by the State of Santa Catarina. (b) Example of four area thresholds for channel initiation tested in this study. (c) Flood hazard maps elaborated by the Civil Defense and Blumenau Prefecture.

**Figure.** 3 The three steps of the f2HAND methodology: (a) flow frequency analysis; (b) HAND raster calculation in a hydrologically consistent DEM; (c) flood hazard map with the probability of a determined pixel to be flooded in any given year calculated by combining flow frequency analysis and the HAND raster.

**Figure 4.** Detailed procedure for matching staff gauge height and the HAND raster. (a), (b) and (c) show the HAND procedure as describe in Rennó et al. (2008) and Nobre et al. (2011). (d) A hypothetical GPS point gathered at a staff gauge that corresponded to the water level of 7 m. That pixel height was 9 m according to the HAND operator. (e) To normalize the water level with the HAND raster, 2 m should be added to the value extracted from the extreme distribution function. (f) Comparison of the direct 10-year return HAND classification and the adjusted height using field information.

**Figure 5.** Annual maxima series for Blumenau, Gaspar and Ilhota stations, and the corresponding fitted distributions for each station.

**Figure 6.** Probable inundation map of Blumenau, Gaspar and Ilhota municipalities using return period (Tr) values calculated with the Gumbel distribution. The zoomed insets show the flood needed to inundate each area and the classified map according to three categories of risk: High (Tr < 5 years), Medium (5 years < Tr < 25 years) and Low (Tr > 25 years).

**Figure 7.** HAND model sensitivity towards drainage generation threshold: performance at Blumenau city centre while varying drainage values and flood hazard map heights using a 10-m resolution DEM.

**Figure 8.** Receiver operating characteristics (ROC) curve for four different official flood hazard maps (10, 11, 12 and 13 m) obtained with a 5-m resolution DEM by varying the channel initiation threshold.

**Figure 9.** Flood map area sensitivity to DEM resolution using Gumbel distribution values for five different DEM resolutions (3, 5, 10, 20 and 30 m).

**Figure 10.** Receiver operating characteristics (ROC) curves for six different DEM resolutions: the SDS 5 m × 5 m, 10 m × 10 m, 20 m × 20 m and 30 m × 30 m provided by SDS and the two SRTM DEMs.

**Figure 11** Percentage accuracy using (a) Gaspar and (b) Ilhota station data distributions in comparison with the Blumenau 2011 flood extent (13 m).
Fig. 1
(a) Official hydrography

(b) Area threshold for channel initiation

Fig. 2

(c) Blumenau official flood hazard maps

20-year flood
15-year flood
8-year flood
5-year flood

T1 = 0.45 km²
T2 = 2.48 km²
T3 = 4.05 km²
T4 = 5.71 km²

Fig. 2
Fig. 3

Fig 4
Fig. 5

Fig. 6
Fig. 7

Area threshold for channel initiation

Flood height

0.45 km$^2$  2.48 km$^2$  4.05 km$^2$  6.71 km$^2$

10 m

11 m

12 m

13 m

True Positive  True Negative  False Positive  False Negative
Fig. 8

Fig. 9
Fig. 10

Fig. 11